UNCERTAINTIES IN PREDICTING AND MEASURING FIELD ERRORS*

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Abstract

Sources of random and systematic field errors in superconducting magnets are described briefly. Predicting such errors in a series production has to rely upon data in prototypes, data in similar magnets, or calculations. The case of D1 insertion dipoles for the LHC perhaps represents the most favorable situation, as these magnets will be almost identical to the RHIC arc dipoles. Uncertainties in predicting field errors for this "best case" are illustrated using data in RHIC dipoles. Once the magnets are built and measured, field quality uncertainties could result from measurement errors and changes in the magnets with quenches and thermal cycles. Such uncertainties are also discussed for the case of RHIC arc dipoles.

1 TYPES OF FIELD ERRORS

The field errors in magnets are generally expressed in terms of the normal (b_n) and skew (a_n) harmonics in a series expansion of the field given by

$$B_y + iB_x = B_0 \times 10^{-4} \sum_{n=1}^{\infty} (b_n + ia_n) \left(\frac{x+iy}{R_{ref}} \right)^{n-1} \qquad (1)$$

where B_0 is a normalizing field and R_{ref} is a reference radius, chosen to be 17 mm in the case of LHC. In this paper, a value of 25 mm will be used frequently for data from RHIC arc dipole magnets. Ideally, for a 2*m*-pole magnet, all coefficients other than $n = m$ should vanish. In practice, several of these coefficients may be non-zero due to design or construction limitations.

For a given production series, the average value of each harmonic will be referred to as the *mean* or *systematic* value of that harmonic. Similarly, the standard deviation of each harmonic over the entire production gives an indication of the extent of variation from one magnet to another and will be referred to as the *random* value of the harmonic. After the magnet production is completed and all the magnets are measured, it is no longer necessary to describe the ensemble of magnets with these statistical parameters for tracking, since the individual data are available, although it may still be a convenient and useful description.

At the pre-production stage, the systematic and the random values of the harmonics are not known. In order to evaluate the impact of field quality that is likely to be achieved in the magnets, one has to make a reasonable estimate of these parameters. Purely based on a good design, the *systematic* values of all the terms unallowed

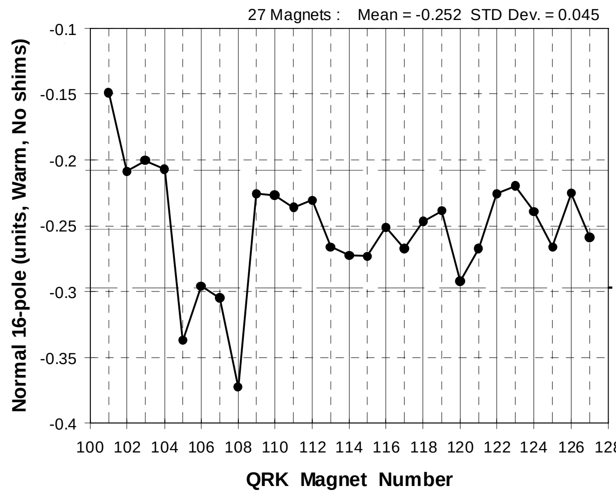

Fig. 1: Example of a non-zero systematic unallowed term.

by symmetry, as well as most of the harmonics allowed by symmetry, are *expected* to be zero. There can be some exceptions to this. For example, it may not be possible to make some higher order allowed terms zero with the available number of adjustable parameters in the coil design. Similarly, in the RHIC arc dipoles, a systematic non-zero value of unallowed skew quadrupole is expected at high fields due to an asymmetric placement of the cold mass in the cryostat [1]. Another example of an anticipated non-zero systematic value of an unallowed harmonic is shown in Fig. 1 for the normal 16-pole term in the 13 cm aperture QRK quadrupoles in RHIC, before the magnetic tuning shims [2] are inserted (R_{ref} = 40 mm).

Although one would like to see the systematic errors in the actual production match the expectations based on design, very often this is not the case due to various reasons. In order to cover such a situation, another parameter, called *uncertainty in the mean*, was used at RHIC. This is an estimate of how much the true systematic value in a given production could deviate from the expected value. This uncertainty is a complex function of tolerances in parts, quality control, production techniques employed, etc.

2 SOURCES OF FIELD ERRORS

2.1 Sources of Random Errors

Random field errors result from random variations in the dimensions of various parts and in other assembly parameters. Other sources of random errors are variations in superconductor parameters, such as magnetization. Such errors can generally be kept to very small values by good quality control at all stages of magnet production. Some lowest order harmonics (both allowed and

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unallowed) may be quite sensitive to construction errors, and may be hard to control. If deemed unacceptable, such errors can be reduced by some type of post construction correction, such as tuning shims [2]. For example, the standard deviation of normal sextupole in as-built QRK quadrupoles for RHIC was 2 units (R_{ref} = 40 mm), but was reduced to 0.4 unit with tuning shims. Changes in the magnet field quality due to thermal cycles and quenches (see Sec. 5.1.4) can also contribute to random errors.

2.2 Sources of Systematic Errors

Systematic errors could be anticipated, or unanticipated. Sources of such errors include:

2.2.1 Design limitations

These are the systematic errors that are anticipated from the design. For example, some high order allowed harmonics may not be made zero with the available number of wedges. Similarly, some unallowed integral harmonics may be non-zero due to inherent asymmetries in the ends. Another example mentioned earlier is the skew quadrupole at high fields in the RHIC arc dipoles.

2.2.2 Calculation limitations

These are generally the low order allowed terms which may result, for example, due to inaccurate modeling of how various turns of the conductor stack up in the coil winding process. Also, there may be some errors in predicting harmonics at high fields due to iron saturation, Lorentz forces, etc.

2.2.3 Tolerances in parts

There may be systematic differences between the "design" and "as-built" parts, within the specified tolerances. These would result in systematic field errors.

2.2.4 Distortions during assembly process

The assembly process could introduce distortions that produce both allowed and unallowed harmonics [3]. For example, the RHIC arc quadrupole yokes were assembled the same way as dipoles, which introduced a large systematic normal octupole harmonic. This was corrected by using asymmetric midplane shims [4].

The systematic errors can be reduced by a careful design, design iterations based on prototypes, small low-cost mid-production corrections if necessary, and post-production corrections such as tuning shims.

3 PREDICTING FIELD ERRORS

Before the magnets are actually built, predicting field errors is of considerable importance from the point of view of tracking studies. Magnet design, production strategies, as well as the correction schemes that may be necessary in the accelerator depend on the outcome of such studies. Obviously, the goal is to arrive at a set of field harmonics, each characterized by a *mean*, *standard deviation* and an *uncertainty in the mean*, which is as close to reality as possible. Too optimistic expectations may not be met in the actual production and could lead to unforeseen loss of performance. On the other hand, expectations of larger harmonic errors may be easily met in production, but could lead to inclusion of correctors that may not really be required. A balancing act in this process involves using as much design and construction experience as possible in making a list of expected harmonics. Also, it will be prudent to reevaluate any large expected field errors if initial tracking studies suggest undesirable effects on the beam. In such cases, every effort should be made to improve the expectations. This could be done by cutting into any unduly comfortable safety margins, and/or by chalking out a contingency plan (small adjustments to shims to fix systematic errors, use of tuning shims to fix both systematic and random errors, etc.) to deal with any large harmonics encountered during production. Such a contingency plan essentially amounts to reducing the "uncertainty in the mean" in the table of expected harmonics. If individual magnets are shimmed, then the random errors are also expected to be reduced.

3.1 Uncertainties in Predicting Field Errors

A key factor in making good predictions of field errors is the availability of good data. Measurements in several prototypes are the most valuable in this process. However, it may not always be feasible to build many prototypes, especially when a production run of only a few magnets is involved. In such cases, estimates have to be based on data in other similar magnets, numerical simulations with random variations in dimensions of various parts, experience with effectiveness of mid course correction strategies, etc. Obviously, the uncertainties in predicting field errors depend on the type of data used, and must be evaluated on a case by case basis.

4 D1 DIPOLES FOR LHC

The superconducting D1 dipoles of 8 cm aperture for the LHC insertion regions perhaps represent the most favorable condition for predicting the field errors. These dipoles are to be built by BNL using the RHIC arc dipole

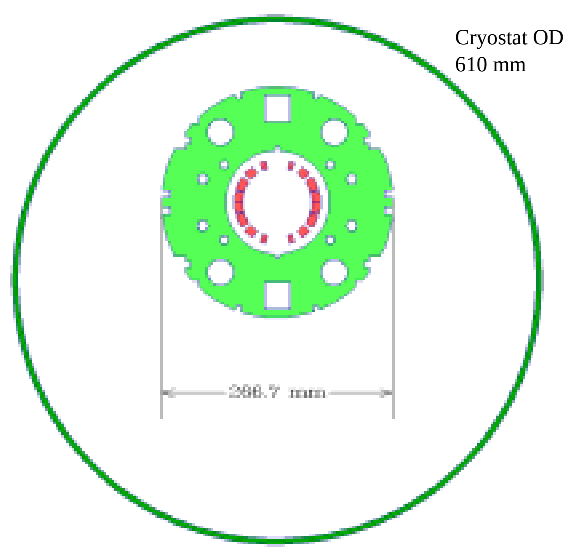


Fig. 2: RHIC arc dipole cold mass inside a cryostat

design, shown schematically in Fig. 2, except that the cold mass will not have a sagitta. Thus, the nearly 300 full length (9.45 m) dipoles in RHIC may be treated as "prototypes" for a production run of only five D1 magnets. In this section, the process of estimating field errors in D1 magnets will be discussed in detail.

4.1 Field Errors (Warm)

All the RHIC dipoles were measured warm, whereas about 20% of the magnets were also measured cold. An example of warm measurement data is shown in Fig. 3, which is a trend plot of the average skew octupole harmonic in the straight section of the 9.45 m long RHIC DRG/DR8 dipoles. As expected for an unallowed term, the mean value is practically zero, and the standard deviation is 0.5 unit. These numbers represent the expected values of systematic and random skew octupole in the D1 magnets (warm). Similar estimates can be obtained for other harmonics.

It is also seen from Fig. 3 that there is a considerable magnet to magnet variation (±1.5 unit) in the skew octupole harmonic. In a new production run with different tooling and with only a few magnets, the mean may not be as close to zero as it is for the RHIC dipoles. This introduces an uncertainty in the mean value. Strictly speaking, it is not possible to deduce this uncertainty from Fig. 3. Nevertheless, the largest deviation from mean seen in any single magnet represents an upper bound for this uncertainty.

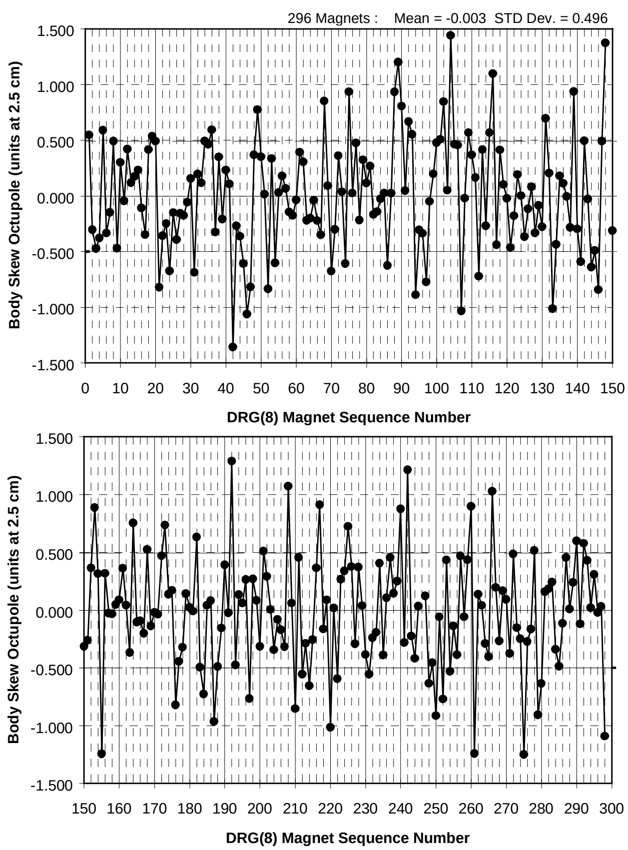


Fig. 3: Trend plot showing skew octupole in the straight sections of 9.45 m long RHIC dipoles.

4.2 Field Errors (Cold)

One is really interested in the field quality under actual operating conditions, rather than the warm harmonics. The harmonics at any magnet excitation can be obtained from the warm values by adding contributions due to warm-cold offsets (if any), contributions due to the superconductor magnetization, and contributions from changes at high fields due to saturation of iron yoke and Lorentz forces. Each of these contributions can be estimated for the D1 magnets from data in RHIC dipoles.

4.2.1 Warm-cold offsets

These are the changes resulting entirely from a change in geometry due to cool down. While most harmonics should not change, some low order allowed terms may be affected. This effect can be estimated by comparing the geometric values (obtained by averaging the values measured during up and down ramps) at intermediate field levels with the warm measurements. Such a comparison is made in Fig. 4 for the normal and skew sextupole terms measured warm and at 1800 A (1.28 T), well above the injection currents of 570 A for RHIC and ~300 A for LHC, but well below onset of saturation. The solid line represents the case of no change between the two measurements. There is no change in the skew sextpole component upon cool down, but the normal sextupole undergoes a systematic change of –0.9 unit. Similar plots can be used to obtain offsets for other harmonics. Table 1 summarizes the systematic changes observed in various harmonics upon cool down. In the table, $\sigma(\Delta b_n)$ and $\sigma(\Delta a_n)$ are the standard deviations representing magnet to magnet variations. These variations introduce an uncertainty in predicting the cold harmonics from the warm harmonics.

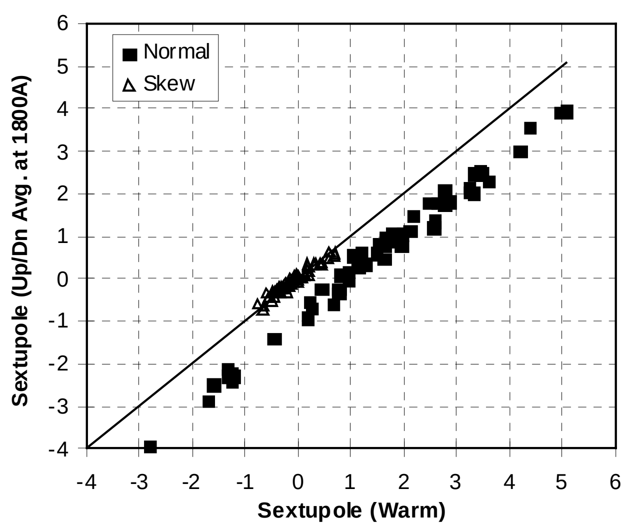


Fig. 4: Geometric values of sextupole harmonics measured cold and warm at the same 1 m long section in RHIC arc dipoles. R_{ref} = 25 mm.

Table 1
Changes in harmonics on cool down in RHIC arc dipoles
(in "units" at 25 mm reference radius)

n*	Δb_n	$\sigma(\Delta b_n)$	Δa_n	$\sigma(\Delta a_n)$
2	–0.22	0.24	0.53	0.59
3	–0.94	0.20	0.03	0.10
4	–0.01	0.08	0.02	0.11
5	0.04	0.08	0.01	0.05
6	0.00	0.04	0.00	0.04
7	–0.05	0.03	0.01	0.02
8	–0.01	0.02	–0.01	0.02
9	–0.01	0.02	–0.01	0.02
10	0.04	0.04	0.03	0.02
11	–0.02	0.01	–0.01	0.01

[* n = 2 denotes the quadrupole term]

4.2.2 Superconductor magnetization

The effect of superconductor magnetization is significant for low order allowed harmonics, particularly at smaller currents. These effects can be estimated from the measured harmonics during the upward and downward ramps of the magnet current. Fig. 5 shows the correlation between sextupole harmonics measured on the up and the down ramps at a current of 300 A (0.21 T field). The solid

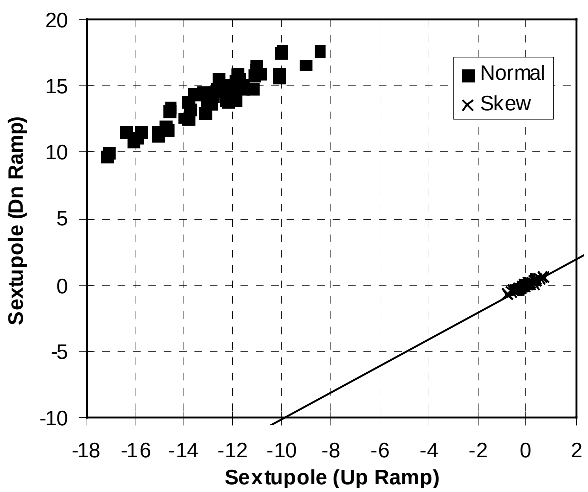


Fig. 5: Correlation between the sextupole terms measured at 300 A (0.21 T) during the "up" and the "down" ramps of a DC loop in RHIC arc dipoles. R_{ref} = 25 mm.

line corresponds to no change in harmonics. While there is no hysteresis effect on the unallowed skew sextupole, the normal sextupole is higher in the down ramp by 26.9 units. The contribution from superconductor magnetization is half of this amount. Similar plots can be used to obtain contributions for all the harmonics. The results are summarized in Table 2 for several fields of interest for D1 dipoles in LHC.

4.2.3 Current dependence of harmonics

As the dipole field is increased, the iron in the yoke begins to saturate. Since the field strength is not uniform

Table 2 Differences between "Down Ramp" and "Up Ramp" harmonics in RHIC arc dipoles. R_{ref} = 25 mm, n = 2 is quadrupole.

n	b_n(Dn) – b_n(Up)			a_n(Dn) – a_n(Up)		
	300A (0.21 T)	5200A (3.52 T)	5800A (3.85 T)	300A (0.21 T)	5200A (3.52 T)	5800A (3.85 T)
2	–0.51	–0.01	–0.01	–0.51	–0.08	–0.01
3	26.90 (σ=0.66)	1.04 (σ=0.13)	0.58 (σ=0.14)	0.04	0.01	0.00
4	–0.02	0.00	0.00	0.15	–0.05	–0.01
5	0.61	0.01	0.04	0.00	0.00	0.00
6	–0.05	0.00	0.00	–0.07	0.00	0.00
7	0.96	0.03	0.03	0.00	0.00	0.00
8	0.02	0.00	0.00	0.02	0.00	0.00
9	–0.19	0.00	0.00	0.00	0.00	0.00
10	–0.02	0.00	0.00	–0.03	0.00	0.00
11	0.25	0.01	0.00	0.00	0.00	0.00

in the yoke, the permeability also no longer remains uniform. Another effect at high fields is a possible deformation of the magnet coil due to high Lorentz forces. These effects introduce additional field errors at high fields. The current dependence of various harmonics is a function of the details of the yoke design and other mechanical factors. The high field behavior of the normal sextupole in RHIC arc dipoles is illustrated in Fig. 6 where values at 1800 A are compared to those at 5200 A and 5800 A in all the magnets that were cold tested. The solid line corresponds to the case of no change in harmonics with current. There is some magnet to magnet variation in the saturation behavior. The results for all harmonics at 5800 A (3.85 T) are summarized in Table 3. The standard deviations, $\sigma(\Delta b_n)$ and $\sigma(\Delta a_n)$, indicate the degree of uncertainty in predicting the saturation behavior for the same magnet design. The uncertainty could be more if a new yoke design, or changes in production parameters are involved. As an example, it is planned to use

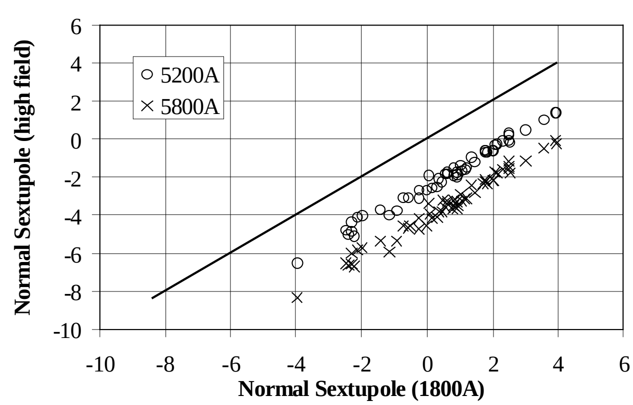


Fig. 6: Correlation between the geometric sextupole terms measured at 1800 A (1.27 T), 5200 A (3.52 T) and 5800 A (3.85 T) in RHIC arc dipoles. R_{ref} = 25 mm.

Table 3 Changes in harmonics at high fields in RHIC arc dipoles. Δb_n and Δa_n are the differences between Up/Dn average values at 5800 A (3.85 T) and 1800 A (1.27 T). R_{ref} = 25 mm

n*	Δb_n	$\sigma(\Delta b_n)$	Δa_n	$\sigma(\Delta a_n)$
2	0.32	0.11	–2.97	1.28
3	–4.12	0.26	–0.11	0.08
4	0.11	0.02	–0.64	0.16
5	–0.19	0.07	–0.02	0.01
6	–0.04	0.05	–0.07	0.03
7	1.14	0.01	0.00	0.00
8	0.00	0.00	0.01	0.01
9	0.02	0.01	0.00	0.00
10	0.01	0.00	0.00	0.00
11	–0.04	0.00	0.00	0.00

steel yoke keys in D1 magnets instead of stainless steel keys used in the RHIC arc dipoles. This would change the high field behavior of the sextupole and the decapole harmonics, thus introducing uncertainties beyond the standard deviations listed in Table 3.

5 UNCERTAINTIES IN MEASURING FIELD ERRORS

Once all magnets in a production series are built and measured, the predictions of field quality, and uncertainties in those predictions, are of limited interest, although for magnet series where less than 100% are cold tested, the uncertainties in predicting cold harmonics from warm harmonics are still of interest. If the measurements were perfect, then the impact of field errors in the as-built magnets can be studied. However, measurement errors contribute to uncertainties in the field errors, which may have to be accounted for in such studies. Thus, an understanding of the uncertainties in the measured harmonics becomes more important at this stage. The measurement errors can be classified as systematic and random.

The systematic and random measurement errors obviously depend on the type of measurement system used, data analysis details, etc. A system of rotating coils, with precision voltmeters or integrators, is the most widely used method to measure field harmonics. In this section, possible sources of systematic errors with such systems will be described briefly.

5.1 Systematic Errors in Measurements

Systematic measurement error in any given harmonic is defined as a deviation of the measured value from the true value. It is difficult to experimentally determine systematic errors, unless a reference magnet with well known harmonics is available. In a recent study, a 18 cm aperture DX magnet for RHIC was used as a reference magnet to “measure” systematic measurement errors in the 10 cm aperture D0 dipoles [5]. In most cases, such a reference magnet is not available and the systematic errors must be estimated based on possible contributions from various sources [6].

5.1.1 Coil construction and calibration errors

A measuring coil of finite length will have random variations of various mechanical parameters, such as radius, angular position, etc. along the length due to construction errors. Such variations will cause a systematic error in harmonic measurements. For two dimensional fields, relatively simple estimates of such measurement errors can be obtained for a variety of coil construction errors. A detailed discussion of this subject can be found in reference [6].

Once a measuring coil is constructed, the accuracy of measurements depends also on the calibration of various geometric parameters. With good calibration techniques, the effect of calibration errors on harmonics can be reduced to negligible levels. Particular care has to be exercised in using long integral coils to measure short magnets. Since the coil parameters can vary along the length due to construction errors, it is important to obtain a calibration for the section of the coil that is actually used.

An analysis of systematic measurement errors for the RHIC arc dipoles can be found in reference [7]. Table 4 summarizes the total systematic error (for typical measuring coil construction errors), as a percentage of the harmonic being measured. The maximum systematic errors in magnets with field quality similar to RHIC arc dipoles can be obtained by applying these percentages to the maximum value of each harmonic observed in these dipoles. These maximum errors, in units at a reference radius of 25 mm, are also listed in Table 4. As can be seen

Table 4 Maximum systematic measurement errors estimated due to coil calibration and construction errors. R_{ref} = 25 mm. Based on reference [7].

n	**Systematic error possible**	**Maximum value of harmonic in RHIC arc dipoles (units)**		**Max. systematic error due to coil calib./constr. (units)**	
		Normal	**Skew**	**Normal**	**Skew**
2	0.78%	1.380	5.881	0.011	0.046
3	1.08%	7.866	1.729	0.085	0.019
4	1.38%	0.293	1.399	0.004	0.019
5	1.68%	1.334	0.335	0.022	0.006
6	1.98%	0.107	0.516	0.002	0.010
7	2.28%	0.527	0.191	0.012	0.004
8	2.59%	0.042	0.143	0.001	0.004
9	2.89%	0.316	0.045	0.009	0.001
10	3.19%	0.019	0.032	0.001	0.001
11	3.49%	0.580	0.015	0.020	0.001
12	3.78%	0.008	0.020	0.000	0.001
13	4.25%	0.214	0.028	0.009	0.001
14	4.74%	0.062	0.046	0.003	0.002
15	5.27%	0.777	0.080	0.041	0.004

from this table, the estimated errors due to coil construction and calibration errors are below 0.1 unit for all harmonics.

5.1.2 Rotational imperfections of measuring coil

The signal from a rotating coil is a function of the coil position and velocity. This can be affected by imperfections such as vibration and wobble of the rotation axis, or angular jitter in data taking. These imperfections give rise to spurious harmonics, or systematic errors. It can be shown [6] that such spurious harmonics can be suppressed by the use of “bucking”. Modern measurement systems invariably incorporate bucking coils for dipole and quadrupole fields, thus eliminating systematic errors due to rotational imperfections in these magnets. However, when such systems are used to measure magnets of a higher multipolarity, the advantages of bucking may not be available. As an example, a systematic decapole harmonic of several units was introduced in the measurements of octupole correctors for RHIC due to lack of octupole bucking.

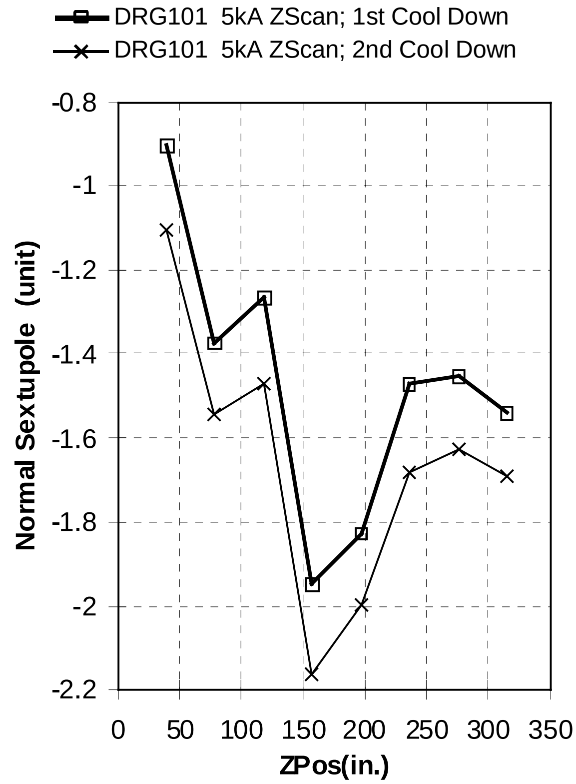
5.1.3 Offset, tilt, sag, etc. of the measuring coil

Even if the rotational axis of the measuring coil has no vibration or wobble, it may not be aligned with the magnetic axis of the magnet. The rotation axis may be displaced uniformly from the magnet axis, or it could be at an angle (tilt), or its position could vary along the length due to sag of the measuring coil. The measured harmonics in such cases differ from the true harmonics due to feed down effects. In most cases, these effects can be minimized by proper “centering” of data. For quadrupoles and higher multipolarity magnets, the magnetic center can be unambiguously defined by feed down from the main harmonic. The centering is not so uniquely defined for dipole magnets. A novel centering technique employing a temporary quadrupole field was used for all RHIC dipoles [8]. This technique provides an unambiguous and precise determination of dipole center. With good centering in a dipole magnet, potential uncertainty in the determination of the quadrupole harmonic due to feed down from large sextupole terms is considerably reduced.

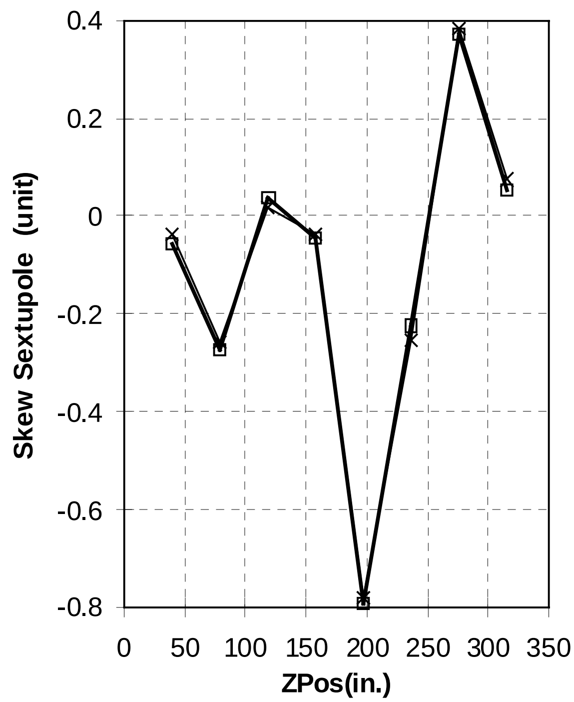
5.1.4 Changes in the magnet itself

During the testing of RHIC magnets, it was found that several harmonics change after the magnet is subjected to quenches and/or thermal cycles [9]. These changes were observed, and studied extensively, in 10 cm aperture D0 dipoles and 13 cm aperture quadrupoles for RHIC. These changes introduce uncertainties in the field errors, even though good measurement data may be available.

Harmonic changes with thermal cycle are available for one RHIC arc dipole, DRG101. Fig. 7 shows the normal and skew sextupole harmonics measured at eight straight section locations in DRG101 at 5kA during two different cool downs. A systematic change of ~0.2 unit is seen in the normal sextupole component after a thermal cycle (Fig. 7a). This change is observed at all axial positions. On the other hand, there is no change in the skew sextupole term (Fig. 7b). This shows that there is an additional measurement uncertainty for the normal sextupole term. The changes in all the harmonics at all the eight positions are shown graphically in Fig. 8. The



(a)



(b)

Fig. 7: Normal and skew sextupole terms measured at 5kA in DRG101 during the first and the second cool downs.

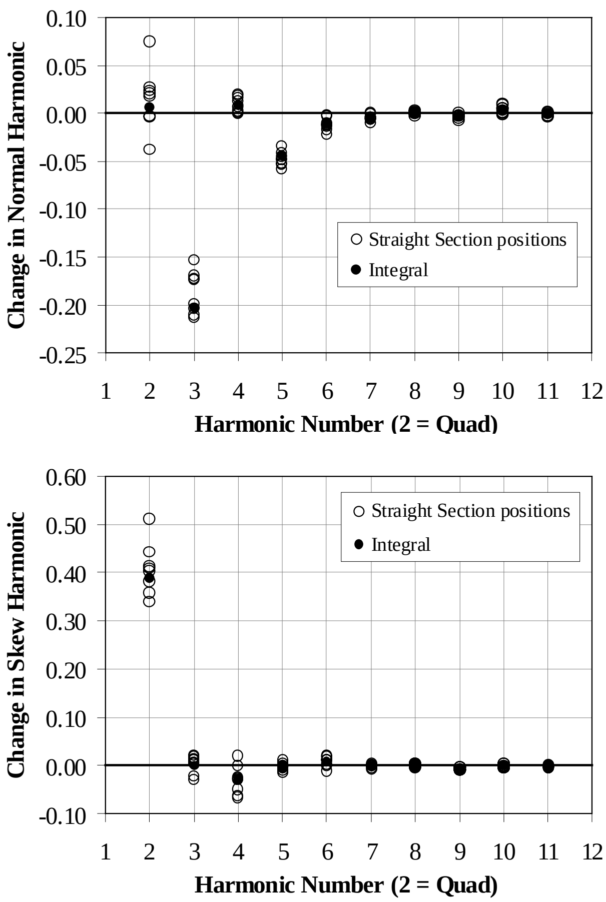


Fig. 8: Changes in the normal and skew harmonics measured at 5kA in DRG101 during the first and the second cool downs. The open circles denote changes at the eight straight section positions and the filled circles denote changes in the integral values.

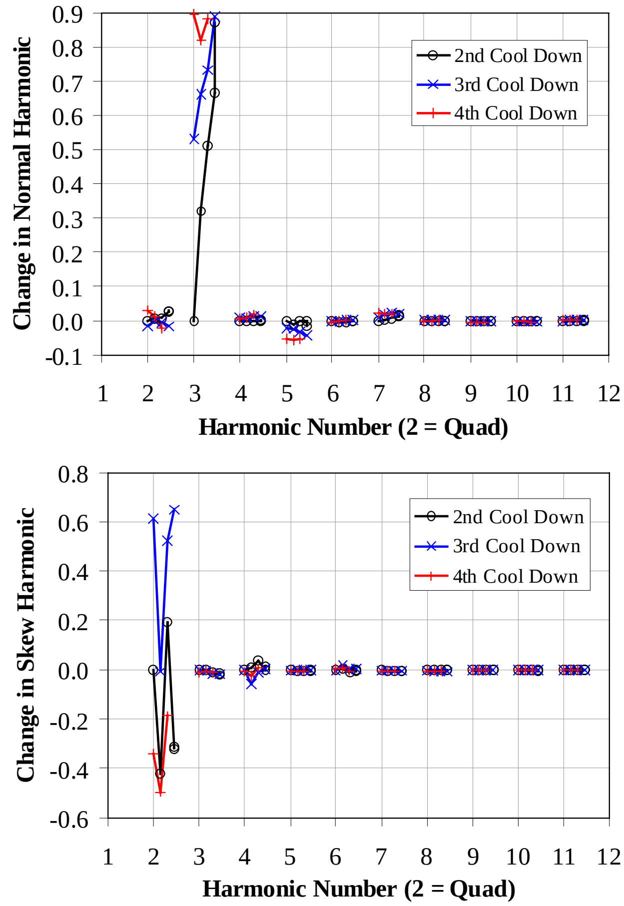


Fig. 9: Changes in the normal and skew harmonics in 10 cm aperture dipole DRZ106 with thermal cycles and quenches. The different points on a curve denote harmonics measured after quenches during the same cool down. R_{ref} = 31 mm.

changes are below 0.1 unit for all harmonics, except the normal sextupole and the skew quadrupole terms.

No data on harmonic changes with quench are available in RHIC arc dipoles. The effect was studied extensively in the 10 cm aperture D0 dipoles for RHIC. Fig. 9 shows the changes in the normal and skew harmonics (at a reference radius of 31 mm) with quenches during three different cool downs. All harmonic changes are calculated with respect to the measurements in the second cool down, before any quenches. The three curves for each harmonic are for the three cool downs. Different points on each curve correspond to measurements after successive quenches. The normal sextupole changes by 0.9 unit as a result of quenches during the second cool down. On a subsequent cool down, there is some recovery, but the new value before quench differs from the very first measurement by 0.5 unit. This trend continues for the fourth cool down, although dependence on quenches now becomes weak. The changes in other harmonics are well below 0.1 unit, except for the skew quadrupole term, which shows variations of up to 0.6 unit. The changes in the arc dipoles with quenches (for which no data exist) are likely to be similar to the D0 dipoles. Clearly, such changes are much larger than the systematic errors of measurement discussed earlier, and represent the largest source of measurement uncertainty. Fortunately, only a couple of terms seem to be affected in the case of dipoles. Several lowest order harmonics could be affected in the case of quadrupoles.

It is believed that the use of plastic spacers in the RHIC magnets may be contributing to changes in conductor positions after thermal cycle and quench. If the magnet coil is well constrained using metal collars, it is likely that the harmonics would not change as much. Limited data in the 18 cm aperture DX dipoles for RHIC, where a stain-less steel collar is used, show that the harmonic changes are indeed smaller. Thus, it may be possible to reduce the uncertainty associated with changes in the magnet itself by choosing an appropriate mechanical design for the magnet.

5.2 Random Errors in Measurements

Random errors in measurements result from inherent system noise and occasional system malfunction. Some harmonics may be affected by stray fields due to magnet leads in the vicinity of the measuring coil. The leads may not always be configured the same way during measurements on different days, thus giving different results.

While one has to generally guess the systematic measurement errors, the random errors can be readily measured by performing multiple measurements on the

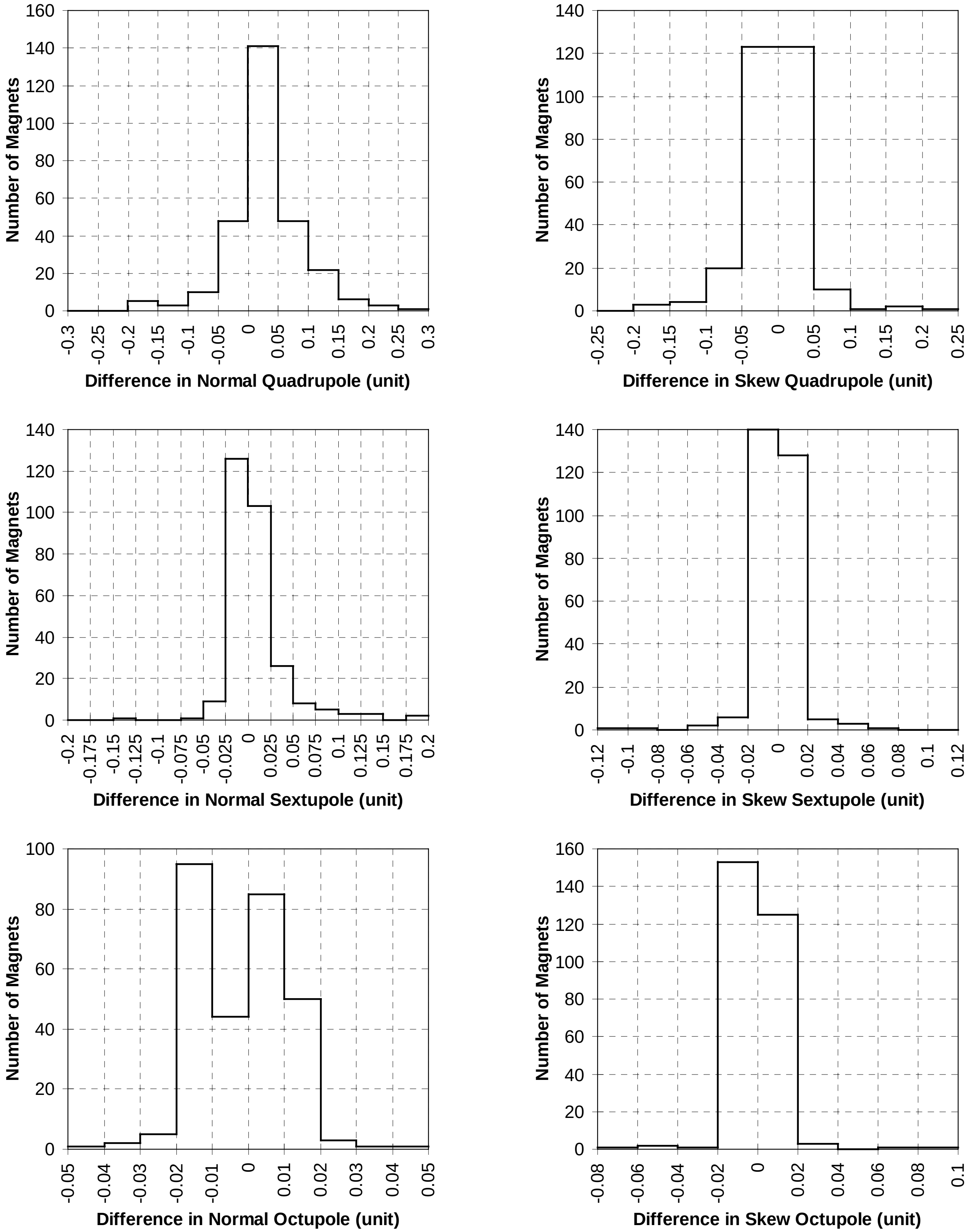


Fig. 10: Distributions of differences between two measurements of warm integral harmonics in 287 arc dipoles. The measurements were carried out using BNL supplied mole equipment at Northrop-Grumman. R_{ref} = 25 mm

same magnet. Such multiple measurements can also help in monitoring the system performance. As an example, two Z-scans were done on all RHIC dipoles at the vendor's location as a means of monitoring reliability of the measurements.

A comparison of the two Z-scans using the same measuring equipment in nearly 300 dipoles gives a good estimate of random errors. Fig. 10 shows the distribution of differences between low order integral harmonics measured in the two Z-scans. For almost all harmonics, the distributions have a strong peak at zero, which means there is practically no systematic difference between the two Z-scans. The standard deviation is the largest (~0.05 unit) for the quadrupole terms, and reduces rapidly for higher order harmonics. The standard deviations for all the harmonics are listed in Table 5. As can be seen from the table, the random errors are practically negligible for all harmonics.

Table 5 Std. Deviations of differences between two integral measurements of harmonics in RHIC arc dipoles.

Harmonic	Std. Dev. of difference in harmonics (units at 25 mm)	
	Normal	**Skew**
Quadrupole	0.061	0.043
Sextupole	0.033	0.015
Octupole	0.012	0.010
Decapole	0.004	0.005
Dodecapole	0.003	0.004
14-pole	0.002	0.002
16-pole	0.001	0.002
18-pole	0.001	0.001
20-pole	0.001	0.001
22-pole	0.001	0.001
24-pole	0.001	0.001
26-pole	0.001	0.001
28-pole	0.002	0.002
30-pole	0.002	0.002

6 SUMMARY

Various sources of systematic and random field errors in superconducting magnets were discussed briefly. Extensive data in RHIC arc dipoles can be used effectively to estimate harmonics in the D1 magnets for LHC, which have a similar design. Uncertainties in predicted harmonics arise mainly from changes in tooling and other magnet parts from one production to another. Additional uncertainties arise due to small uncertainties in the estimation of various contributions to harmonics at any given operating point. Once all the magnets are built and measured, uncertainties in field quality are governed by measurement errors and changes in the magnet itself after thermal cycles and quenches. The true measurement errors, both systematic and random, have been shown to be negligible in the case of RHIC. Thus, uncertainties in our knowledge of the field quality of the magnets installed in the accelerator arise primarily from the changes in the magnets themselves.

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